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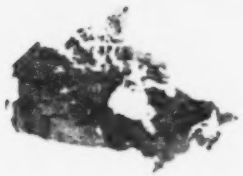

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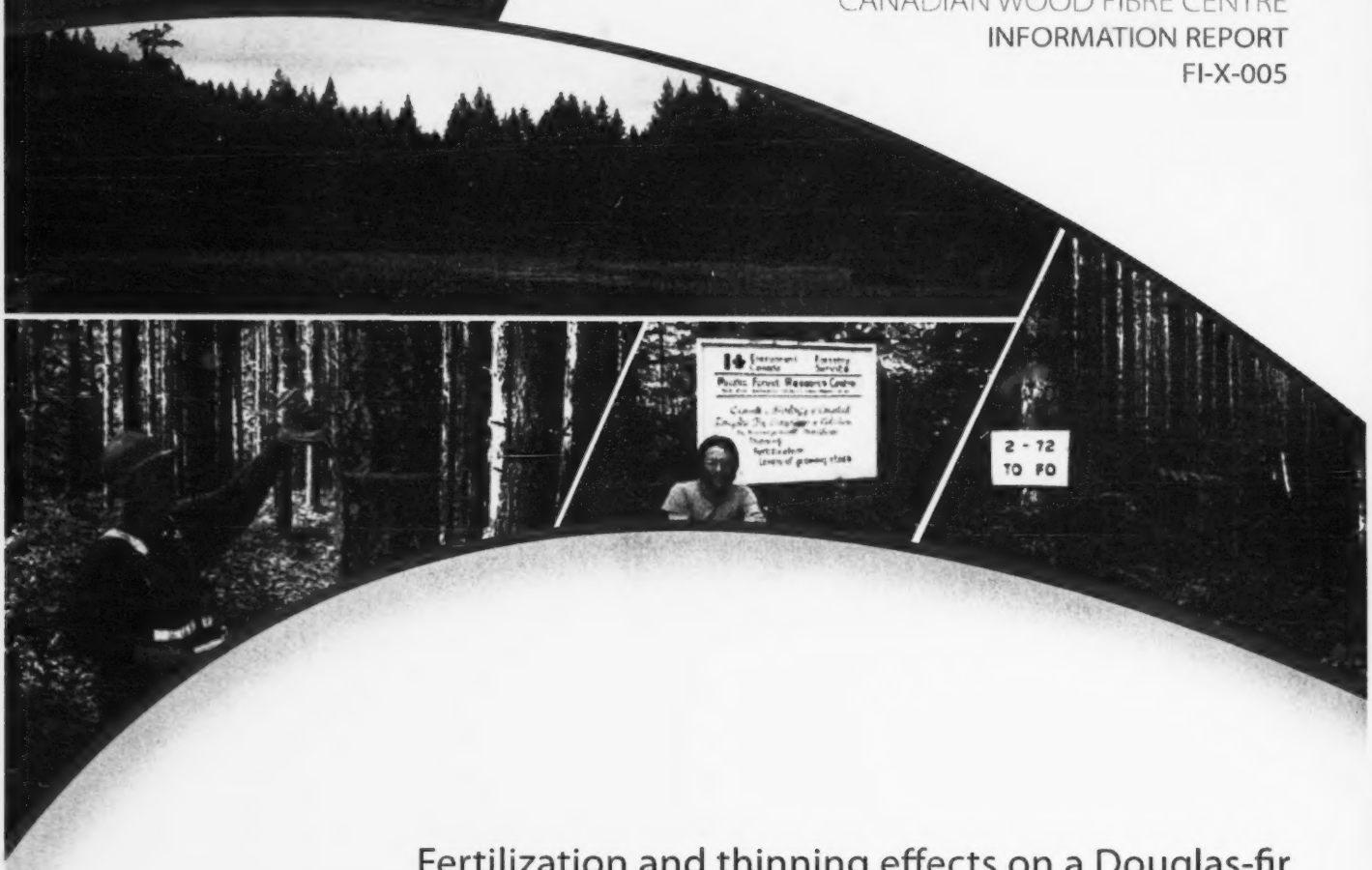

Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 32-year growth response

A.Y. Omule, A.K. Mitchell, and W.L. Wagner

Canada

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Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 32-year growth response

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Executive Summary

The Canadian Forest Service's Shawnigan Lake Project (SLP) main experiment was established in 1971–1972 to study the effects of fertilizing and thinning 24-year-old coastal Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) on a dry and nutrient-poor site (Site index 25 m at 50 years breast height age). It consists of three levels of thinning and five levels of fertilization, including the controls. The thinning levels (single entry) are: no thinning (T0), 1/3 basal area removed (T1), and 2/3 basal area removed (T2). The fertilization levels are: no fertilization (F0), application of 224 kg N/ha once (F1) or thrice (F1-1-1), and application of 448 kg N/ha once (F2) or twice (F2-2). The second application of fertilizer was done in 1981 and the third in 1990. Each thinning and fertilization treatment combination consists of two or four 0.0405-ha plots, totalling 36 plots. These plots were remeasured nine times over a 32-year period.

Plot average and per-hectare tree data were pooled by treatment and analyzed separately for the entire stand and crop trees. Crop trees (or prime trees) represented the largest 250 trees per ha at time of treatment that were still alive 32 years after treatment. The treatment effects were compared using the fixed-effects model, for 32-year periodic annual increment (PAI) and yield 32 years after treatment, for various stand attributes. The stand attributes included quadratic mean DBH (QMD), arithmetic average height (AAH), and total and merchantable volume.

The analysis results were generally consistent with our expectations. The results showed the following:

1. Cumulative mortality over the 32-year period since the initial treatment was highest in the T0 and T1 treatments, and negligible in the T2. The main cause of mortality continues to be suppression, although snow damage was also prevalent. Thus, thinning can be beneficial by capturing the volume from trees that would otherwise have been lost to mortality, if the thinned fibre can be used.
2. Fertilization increased stand and crop tree diameter and height PAI in both thinned and unthinned stands, with greatest growth in the T2F2-2 treatment.
3. Thinning also increased quadratic mean DBH (QMD) and arithmetic average height (AAH) periodic annual increment (PAI), and shifted stand basal area to fewer, larger-diameter trees. However, part of this increase in QMD and AAH is due to the arithmetic increase in average diameter or height resulting from the removal of smaller-than-average trees from thinning and mortality.
4. Heavy thinning increased the live crown length, and fertilization slightly decreased the live crown length. That is, the amount of clear bole is reduced by the heavy thinning. If the management objective is lumber production, thinning may have to be combined with pruning to reduce the size and number of knots on the bole.
5. Fertilization increased production of stand and crop tree total and merchantable wood volume fibre in both thinned and unthinned stands, with the greatest growth in the F2-2 treatment. For example, the total volume PAI responses relative to F0 ranged from 26% (F1) to 55% (F2-2). However, the F1 treatment was the most efficient in terms of total volume PAI per kg N/ha.
6. Thinning did not have a significant effect on stand total and merchantable volume production, although heavy thinning significantly increased crop tree total and merchantable volume PAI. However, the stand volume results are confounded by post-treatment volume differences, the slower growth of more numerous smaller trees in the unthinned plots, and the faster growth of fewer larger trees in the thinned plots. The ranking of total volume/ha at 32 years was T0 > T1 > T2, although the gap between total volume in the thinned and the unthinned stands is narrowing.

These 32-year results added to the information base supporting informed forest management decision-making in coastal British Columbia, and contributing to the Canadian Wood Fibre Centre's initiative of promoting research on the effect of silviculture and stand dynamics on fibre attributes. These results may be extended to similar dry and nutrient-poor sites on the coast and will also contribute to our knowledge of the response of coastal Douglas-fir stands to thinning and fertilization. To confirm the conclusions to date, and to provide more complete plot histories, continued remeasurement of the SLP plots is recommended.

Sommaire

Le Service canadien des forêts a amorcé en 1971–1972 l'expérience principale de son projet du lac Shawnigan (PLS) afin d'étudier les effets de la fertilisation et de l'éclaircie sur des peuplements côtiers de douglas (*Pseudotsuga menziesii* [Mirb.] Franco) de 24 ans poussant dans un sol sec et pauvre en éléments nutritifs (indice de station de 25 m à 50 ans à hauteur de poitrine). L'expérience comportait trois intensités d'éclaircie et cinq niveaux de fertilisation, y compris des placettes témoins. Les trois intensités d'éclaircie (passage unique) étaient les suivantes : aucune éclaircie (T0), 1/3 de la surface terrière éliminé (T1), 2/3 de la surface terrière éliminés (T2). Les niveaux de fertilisation étaient les suivants : aucune fertilisation (F0), application de 224 kg N/ha à une (F1) ou trois (F1-1-1) reprises, application de 448 kg N/ha à une (F2) ou deux (F2-2) reprises. La deuxième application d'engrais a été effectuée en 1981 et la troisième, en 1990. Deux ou quatre placettes de 0,0405 ha ont été affectées à chaque combinaison de traitements d'éclaircie et de fertilisation, pour un total de 36 placettes. Des mesures ont ensuite été prises à neuf reprises dans chaque placette au cours d'une période de 32 ans.

Les données sur les arbres (moyennes établies par placette et par hectare) ont été regroupées par traitement et analysées séparément en fonction du peuplement entier ou des arbres d'avenir. Ont été désignés arbres d'avenir (ou arbres de qualité supérieure) les 250 sujets de plus fortes dimensions par ha au moment du traitement et encore vivants 32 ans plus tard. Les effets des traitements sur l'accroissement annuel périodique de 32 ans et le rendement 32 ans après le traitement ont été comparés à l'aide du modèle à effets fixes pour divers attributs de peuplement, y compris le DHP moyen quadratique (DMQ), la hauteur moyenne arithmétique (HMA) et le volume total et marchand.

De façon générale, les résultats de l'analyse se sont révélés conformes à nos attentes. Nos constats sont les suivants :

1. La mortalité cumulative au cours des 32 ans écoulés depuis le traitement initial était maximale dans les traitements T0 et T1, négligeable dans le traitement T2. La principale cause de mortalité demeure l'oppression exercée par les arbres dominants, quoique les dommages causés par la neige étaient également importants. L'éclaircie peut donc avoir des effets bénéfiques en permettant de sauvegarder la matière ligneuse d'arbres qui seraient autrement morts, pour autant que ces fibres ligneuses puissent être utilisées.
2. La fertilisation a eu un effet positif sur l'APM du diamètre et de la hauteur des arbres du peuplement et des arbres d'avenir dans les peuplements tant éclaircis que non éclaircis. La plus forte croissance a été observée dans le traitement T2F2-2.
3. L'éclaircie a également stimulé l'accroissement périodique moyen (APM) du diamètre moyen quadratique (DMQ) et de la hauteur moyenne arithmétique (HMA) et transféré la surface terrière des peuplements vers un plut petit nombre de sujets de plus fort diamètre. Toutefois, une partie de l'augmentation du DMQ et de l'HMA est due à l'augmentation arithmétique du diamètre ou de la hauteur moyenne des arbres occasionnée par l'élimination des sujets de taille inférieure à la normale par les éclaircies et la mortalité.
4. L'éclaircie forte a fait augmenter la longueur de la cime vivante, tandis que la fertilisation l'a fait légèrement diminuer. En d'autres mots, l'éclaircie forte a causé une réduction du volume de fût net. Si l'aménagement vise la production de bois de sciage, il pourrait être nécessaire de jumeler éclaircie et élagage pour réduire la taille et le nombre de nœuds sur le fût.
5. La fertilisation a permis d'accroître la production de volume ligneux total et marchand des arbres d'avenir et des peuplements tant éclaircis que non éclaircis. La plus forte croissance a été enregistrée dans le traitement T2F2-2. À titre d'exemple, en comparaison des valeurs enregistrées dans le traitement F0, l'APM du volume total a oscillé entre 26 % dans le traitement F1 et 55 % dans le traitement F2-2. C'est toutefois le traitement F1 qui a induit le plus fort APM du volume total par kg N/ha.
6. L'éclaircie n'a pas eu d'effet significatif sur la production de volume total et marchand des peuplements, mais l'éclaircie forte a entraîné une hausse significative de l'APM du volume total et marchand des arbres d'avenir. Toutefois, les différences post-traitement de volume, la croissance plus lente des petits sujets plus nombreux dans les placettes non éclaircies et la croissance des sujets de fortes dimensions moins nombreux dans les placettes éclaircies vont à l'encontre des résultats sur les volumes des peuplements. Les valeurs de volume total/ha observées 32 ans après le traitement initial s'établissaient comme suit : T0 > T1 > T2. Il convient toutefois de noter que les différences observées à ce chapitre entre les peuplements éclaircis et les peuplements non éclaircis s'amenuisent.

Ces résultats compilés durant ces 32 ans contribuent à enrichir la base de données à l'appui de la prise de décisions éclairées en matière d'aménagement des forêts dans les régions côtières de la Colombie-Britannique et de l'objectif du Centre canadien sur la fibre de bois de promouvoir la recherche sur les effets des pratiques sylvicoles et de la dynamique des peuplements sur les attributs des fibres ligneuses. Ces résultats peuvent être étendus à d'autres peuplements occupant des sites côtiers secs et pauvres en éléments nutritifs similaires et nous aideront à mieux comprendre la réaction des peuplements côtiers de douglas à l'éclaircie et à la fertilisation. Pour confirmer les conclusions atteintes à ce jour et mieux caractériser l'évolution des placettes expérimentales, il est recommandé de continuer de prendre des mesures dans les placettes établies dans le cadre du projet du lac Shawinigan.

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Acronyms

AAD	Arithmetic Average DBH
AAH	Arithmetic Average Height
BCFSP	British Columbia Forest Science Program
CFS	Canadian Forest Service
DBH	Tree Diameter at Breast Height
HTLC	Tree Height to Live Crown
PAI	Periodic Annual Increment
PFC	Pacific Forestry Centre
QMD	Quadratic Mean DBH
SLP	Shawnigan Lake Project

1. Introduction

The objective of the Shawnigan Lake Project (SLP), which was initiated in 1970, is to study the mechanisms of response to thinning and fertilization. The SLP study is composed of two components: a) the main experiment, and b) subsidiary studies. The main experiment established, in 1971–1972 (36 plots), investigated the effects of thinning and fertilization, and consisted of three levels of thinning and five levels of fertilization, including controls. The subsidiary studies include (1) a study established in 1972–1973 (14 plots) to investigate the effects of higher doses of Nitrogen (N), and to compare the effects of ammonium nitrate and urea as nitrogen sources, on stand growth (SUB1); (2) a study established in 1983 (2 plots) to investigate the effects of thinning on water use and soil water (SUB2); and (3) a study established in 1987 (8 plots) to investigate the additional growth response of thinned stands to fertilization with Phosphorous (P) and Sulphur (S) along with N (SUB3). This report focuses only on the main experiment.

Several published reports based on this project have documented tree and stand responses to thinning and fertilization (Brix 1993). The growth and yield reports from the SLP main experiment include Crown and Brett (1975), Crown et al. (1977), Hall et al. (1980), Barclay et al. (1982), Barclay and Brix (1985), Gardner (1990), and McWilliams and Therién (1996; revised 1997).

This report focuses on the 32-year growth response for selected stand attributes. It is based on the detailed report prepared for the British Columbia Forest Science Program (BCFSP) (Omule 2008). Detailed tabulation of the treatment statistics and comparisons of other stand attributes not reported here, such as stand basal area, are given in Omule (2008). Section 2 describes the study area and experimental design; section 3 describes the database; section 4 outlines the analysis methods; section 5 provides the study results; section 6 discusses the results; and the last section provides some conclusions. Information in sections 2 and 3 is reported elsewhere (e.g., Brix 1993; Crown and Brett 1975), but it is repeated here for easy reference.

2. Study Area and Experimental Design

2.1 Study Area

The SLP study area is located approximately 5 km west of the north end of Shawnigan Lake on southeastern Vancouver Island, British Columbia. The study site, covering an area of about 50 ha, is located within the very dry maritime Coastal Western Hemlock biogeclimatic subzone (CWHxm1, site series 03 FdHw–salal). It consists of moderately dry, nutrient-poor to -medium ecotopes. Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) is the dominant species, mixed with a minor component of western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), western redcedar (*Thuja plicata* Donn), western white pine (*Pinus monticola* Dougl.), and lodgepole pine (*Pinus contorta* Dougl.). Salal (*Gaultheria shallon* Pursh) is the major understorey species.

At the time the study was established:

- The stand total age was 24 years for the stand component that originated from planting two-year-old Douglas-fir seedlings in the spring of 1948, and was less than 13 years of age for the naturals.
- The Douglas-fir site index was 25 m at breast height age 50 years, based on Bruce's (1981) site index curves.
- The average stand density was approximately 3950 stems/ha, and the average tree diameter and height were 7.6 cm and 8.6 m respectively.

2.2 Experimental Design

The design of the main experiment, as originally established in 1971–1972, was a 3 × 3 factorial in a completely randomized design. There were three levels of thinning (T0, T1, T2) and three levels of fertilization (F0, F1, F2), resulting in nine treatment combinations. The T0 and F0 levels are the controls; the T1 treatment consisted of stands with 1/3 of the basal area removed, and the T2 treatment had 2/3 of the basal area removed. The F1 and F2 treatments were fertilized with 224 and 448 kg N/ha respectively. Each treatment combination was applied to four plots (replicated) for a total of 36 plots (Table 1). The 36 plots were established over a two-year period: 18 plots in 1971 and 18 plots in 1972.

Table 1. Original experimental design: Levels of thinning and fertilization and number of plots per treatment combination.

Thinning levels	Fertilization levels		
	F0	F1	F2
T0	4	4	4
T1	4	4	4
T2	4	4	4

In 1981, 9 years after the first treatments, the plots initially fertilized in 1972 (F1 and F2) were re-fertilized at their original rates (F1-1, F2-2). In 1990, 18 years after the first treatments, the F1-1 plots re-fertilized at 9 years were fertilized a third time (F1-1-1); however, the F2-2 level plots were not fertilized again. The end result is a total of 15 treatment combinations—three levels of thinning and five levels of fertilization—with a varying number of plots per treatment combination (Table 2).

All plots are square, 0.0405 ha in area, and surrounded by a 15-m-wide treated buffer. The thinning treatments were carried out in the fall and winter of 1970 and 1971 for the 1971 and 1972 plots respectively. Thinning aimed to leave an even spacing of residual trees, which were adequately represented across a range of diameter classes. It eliminated advanced natural regeneration or "wolf" trees. Nitrogen in the form of forest-grade urea was uniformly applied within a plot by hand-broadcast after thinning in March of 1971 and 1972, and in 1981 and 1990.

Table 2. Modified experimental design: Levels of thinning and fertilization and number of plots per treatment combination.

Thinning Levels	Fertilization Levels				
	F0	F1	F1-1-1	F2	F2-2
T0	4	2	2	2	2
T1	4	2	2	2	2
T2	4	2	2	2	2

3. Tree Data and Plot Summaries

Measured tree variables for growth and yield purposes included tree diameter at breast height (DBH), total height, and height to live crown (HTLC). These variables were measured on all core trees (trees within the 0.0405-ha plot; DBH > 2.5 cm) at 0, 3, 6, 9, 12, 15, 18, 24, and 32 years after plot establishment. The most recent remeasurement, 32 years after plot establishment, was completed in 2002–2003. Tree heights and HTLC were measured in only a sub-sample of the core trees after the ninth year. These height sample trees were randomly chosen from diameter classes to ensure that heights were taken across the full range of diameters.

Derived tree variables included unmeasured tree heights, and total and merchantable volume. Unmeasured tree heights were estimated from height–diameter curves fitted to the height sample data for each plot and measurement period separately. Total and merchantable volumes of all tree species, including the minor tree components, were estimated from the existing Douglas-fir equations (Omule et al. 1987). Total volume is whole stem, inside bark, and DBH over 2.5 cm. Merchantable volume is total volume less the volume of a 30-cm-tall stump and a 10-cm diameter inside bark tree top, with a minimum DBH of 12.5 cm.

The individual tree measurements and derived variables were summarized into plot average and per-hectare values, for the entire stand and crop trees (or prime trees). The crop trees were the largest 250 trees per hectare (or 10 trees per plot); they represent the number of trees recommended to be left after commercial thinning in coastal British Columbia (Gardner 1990). The chosen crop trees were live Douglas-fir at year 32 that had the largest DBH at the time of treatment.

Net 32-year periodic annual increment (PAI) and yield 32 years after treatment were calculated for each plot for various stand attributes, for the entire-stand, and for the crop trees. The PAI was calculated as the difference between the standing (net) value at the initial (post-treatment) measurement and the standing value at the latest remeasurement divided by 32 years. The standing value at the latest remeasurement corresponded to the yield at 32 years after treatment. The stand and crop tree attributes included quadratic mean diameter (QMD), arithmetic average height (AAH), and total and merchantable volume. The average diameter and height increments of trees surviving to year 32 were also calculated by initial 5-cm DBH classes for each plot. This was to enable the examination of the effects of thinning and fertilization on diameter and height growth of trees with different initial sizes.

4. Data Analysis

For this report, analysis closely mimicked that used in the 15-year and 24-year growth response reports, so the results could easily be compared. The analysis involved statistical comparison of treatment means and calculation of treatment means adjusted for differences in pre-treatment stand conditions. The average 32-year PAI and yield 32 years after treatment among the treatments were compared for various attributes at the 95% probability level ($p < 0.05$).

The treatments were compared using a fixed-effects model. The model's dependent variable was either the PAI or the yield 32 years after treatment, and the fixed effects were the thinning treatments (T0, T1, T2), fertilization treatments (F0, F1, F1-1-1, F2, F2-2), the interaction between thinning and fertilization treatments, and the appropriate pre-treatment stand values as covariates. The stand attributes included quadratic mean DBH, mean height, total volume, and merchantable volume.

The mathematical form of the model used was:

(1) $y_{ijk} = \mu + T_i + F_j + T_iF_j + X_{ijk} + \varepsilon_{ijk}$

where μ is the overall mean, y_{ijk} represents the observation in k^{th} plot in the i^{th} thinning (T) level in the j^{th} fertilization (F) level; X_{ijk} is a pre-treatment value covariate; and ε_{ijk} is the random error associated with the k^{th} plot.

The fixed-effects model (1) was fitted using the SAS® PROC MIXED procedure, and adjusted treatment means were generated using the LSMEANS statement (Little et al. 1996). The analyses were done on a land area basis for average individual tree size, trees of similar initial size, and crop trees.

5. Results

5.1 Mortality

Mortality was highest in the T0 and T1 treatments and lowest in the T2 treatment. The main cause of mortality in the T0 and T1 treatments appears to be suppression (Table 3).

Fertilization presumably increased the impact of suppression. Snow damage was also prevalent in the T0 and T1 treatments.

Mortality was highest in the 5-cm and 10-cm initial DBH classes (Table 4).

The highest mortality was in the T0F1-1-1 treatment (61% stems/ha), and the lowest was in the T2F0 treatment (1% stems/ha). As a result of the mortality, the number of residual stems per hectare in the unthinned stands 32 years after treatment is only about 40–56% of the original density (Table 5).

Table 3. Cumulative mortality (stems/ha) from various causes, 32 years after initial treatment.

Treatment	Cause of Mortality						
	Suppression	Snow Damage	White Pine Blister Rust	Root Rot	Mechanical	Unknown	Total
T0F0	1907	49	12	19	19	142	2148
T0F1	1321	99	-	-	-	148	1568
T0F2	1704	25	25	25	-	222	2001
T0F1-1-1	2000	235	12	-	-	12	2259
T0F2-2	1259	160	49	25	-	12	1505
T1F0	253	80	-	25	-	37	395
T1F1	222	111	-	-	-	12	345
T1F2	259	37	-	-	-	99	395
T1F1-1-1	321	49	12	25	-	-	407
T1F2-2	605	160	-	25	-	12	802
T2F0	6	12	-	-	-	-	18
T2F1	-	50	-	-	12	-	62
T2F2	-	-	-	-	12	-	12
T2F1-1-1	12	62	-	12	-	-	86
T2F2-2	25	37	-	-	-	-	62

Table 4. Cumulative mortality (stems/ha), by 5-cm initial DBH classes and treatment, 32 years after initial treatment.

Treatment	5-cm Initial DBH Class				Total
	5	10	15	20	
T0F0	1809	321	12	6	2148
T0F1	1198	370	-	-	1568
T0F2	1852	149	-	-	2001
T0F1-1-1	1321	914	12	12	2259
T0F2-2	975	518	12	-	1505
T1F0	228	167	-	-	395
T1F1	185	148	12	-	345
T1F2	309	86	-	-	395
T1F1-1-1	247	160	-	-	407
T1F2-2	321	469	12	-	802
T2F0	-	18	-	-	18
T2F1	25	25	12	-	62
T2F2	-	12	-	-	12
T2F1-1-1	25	49	12	-	86
T2F2-2	37	25	-	-	62

Table 5. Number of live trees (stems/ha) in different classes of years after initial treatment.

Treatment	Years After Treatment									
	0 (Before)	0 (After)	3	6	9	12	15	18	24	32
T0F0	4839	4839	4784	4722	4611	4482	4272	3939	3420	2691
T0F1	3568	3568	3531	3457	3371	3149	2975	2691	2371	2000
T0F2	4037	4037	3976	3629	3321	3061	2852	2692	2346	2037
TOF1-1-1	3680	3680	3556	3260	3037	2803	2519	2049	1753	1420
T0F2-2	3222	3222	3186	2939	2741	2519	2260	1939	1877	1716
T1F0	4352	1969	1957	1951	1938	1938	1920	1895	1790	1574
T1F1	3469	1815	1815	1803	1791	1778	1716	1679	1593	1469
T1F2	4099	2013	2013	1963	1939	1914	1914	1864	1778	1618
T1F1-1-1	3753	1889	1889	1889	1889	1852	1803	1679	1531	1482
T1F2-2	3828	2087	2087	2037	1976	1902	1765	1580	1469	1284
T2F0	3772	895	895	895	895	895	895	895	895	877
T2F1	3926	939	939	939	939	939	914	914	902	877
T2F2	3679	914	914	914	914	914	914	902	902	902
T2F1-1-1	3753	889	877	877	877	877	865	865	865	803
T2F2-2	4037	877	865	865	865	865	852	840	840	815

5.2 Diameter

5.2.1 Stand Diameter

Treatment differences in stand diameter were assessed in terms of quadratic mean DBH (QMD). Note that the differences in QMD are the result of the growth of survivor trees, tree mortality, and thinning. There is an immediate arithmetic effect when trees die or are thinned. If the trees removed are smaller in diameter than the average, the overall average QMD will increase, and if the trees removed are larger than the average, the overall average QMD will decrease.

The comparison of the treatment QMD periodic annual increment (PAI) and 32-year QMD showed that (Table 6):

1. There was no significant interaction between thinning and fertilization.
2. Both thinning and fertilization had a significant effect on QMD PAI and 32-year QMD. The QMD PAI and 32-year QMD increased with an increase in thinning intensity and with an increase in fertilizer dosage (Figures 1 and 2). Thinning alone increased QMD PAI and 32-year QMD more than fertilization alone.
3. The adjusted QMD PAI treatment means ranged from 0.26 cm/yr (T0F0) to 0.56 cm/yr (T2F2-2), and the 32-year QMD treatment means ranged from 17.0 cm (T0F0) to 29.3 cm (T2F2-2).

Table 6. Probability values (p) from the fixed-effects model analysis testing differences in treatment means for various stand attributes. (The significance level was $p < 0.05$.)

	Entire Stand		Crop Tree
	PAI	**32-year Yield**	**PAI**
Quadratic Mean DBH (QMD)			
Thinning	< 0.0001	< 0.0001	< 0.0001
Fertilization	< 0.0001	< 0.0001	< 0.0001
Thinning x Fertilization	0.5497	0.4036	0.9909
Pre-treatment QMD	0.0012	< 0.0001	0.3481
Arithmetic Average Height (AAH)			
Thinning	0.0006	< 0.0001	< 0.0010
Fertilization	< 0.0001	< 0.0001	< 0.0001
Thinning x Fertilization	0.4152	0.4779	0.7395
Pre-treatment Average Height	0.0384	0.0006	< 0.1021
Stand Total Volume			
Thinning	0.3743	0.0745	0.0007
Fertilization	< 0.0001	< 0.0001	< 0.0001
Thinning x Fertilization	0.9410	0.9699	0.0976
Pre-treatment Total Volume	0.0109	0.0062	< 0.0001
Stand Merchantable Volume			
Thinning	0.5975	0.7740	< 0.0001
Fertilization	< 0.0001	< 0.0001	< 0.0001
Thinning x Fertilization	0.9113	0.8755	0.0327
Pre-treatment Merchantable Volume	0.0012	0.0003	< 0.0001

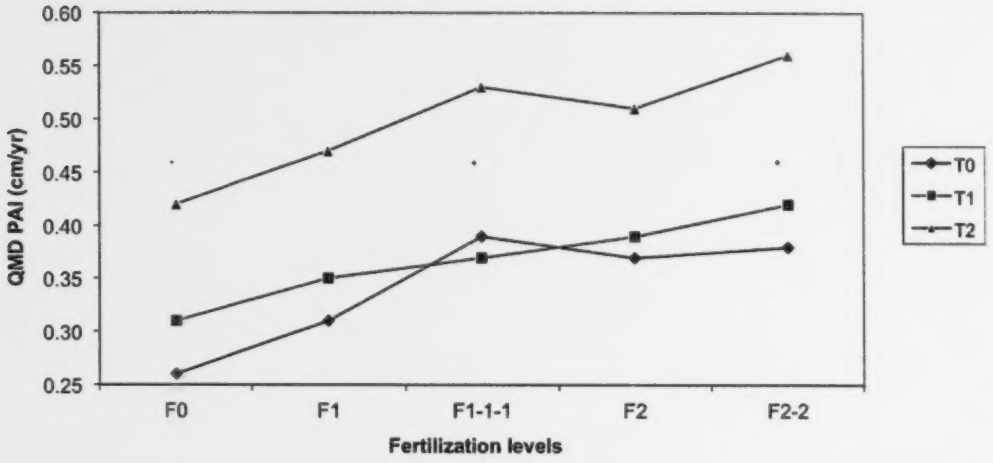

Figure 1. Adjusted quadratic mean DBH (QMD) periodic annual increment (PAI) treatment means for each treatment.

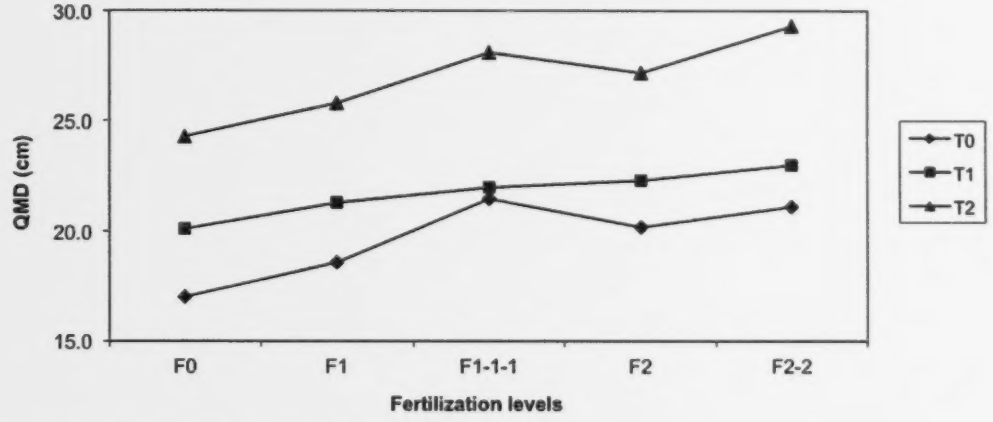

Figure 2. Adjusted quadratic mean DBH (QMD) treatment means 32 years after treatment for each treatment.

5.2.2 Trees of Similar Initial Diameter Classes

Thirty-two-year periodic increments of arithmetic average diameter (AAD) for surviving trees are summarized by initial 5-cm DBH classes and treatment in Tables 7 and 8.

These data showed that:

1. In all treatments, AAD periodic increment increased with increasing initial diameter classes.
2. Relative to the unthinned control (T0), and for a given DBH class, AAD growth was higher in the thinned treatments, with the smallest trees having the greatest relative growth (Table 8).
3. Within each thinning level, AAD growth was greater at higher fertilizer dosages.

Table 7. Arithmetic average DBH increments (cm/32 years) of surviving trees by initial 5-cm DBH classes.

Treatment	5-cm DBH Class				
	5	**10**	**15**	**20**	**25**
T0F0	2.6	6.0	11.0	16.5	20.6
T0F1	3.6	7.1	12.7	15.6	-
T0F2	6.0	9.2	14.9	-	-
T0F1-1-1	2.5	9.0	13.7	20.2	22.8
T0F2-2	6.5	9.7	16.0	-	-
T1F0	4.2	8.5	12.4	12.9	17.6
T1F1	5.4	10.2	15.1	-	-
T1F2	6.3	11.3	14.4	16.9	-
T1F1-1-1	6.3	10.4	14.4	-	19.4
T1F2-2	7.0	11.8	15.8	22.0	-
T2F0	10.0	12.3	15.7	19.4	-
T2F1	9.3	14.4	18.7	-	-
T2F2	11.5	16.1	18.2	-	-
T2F1-1-1	11.8	15.7	21.4	21.8	-
T2F2-2	11.4	17.1	20.0	22.4	-

Table 8. Arithmetic average DBH relative increments (% gain over the control) of surviving trees by initial 5-cm DBH classes.

Treatment	5-cm DBH Class				
	5	**10**	**15**	**20**	**25**
T0F0	0	0	0	0	0
T0F1	38	18	15	-5	-
T0F2	131	53	35	-	-
T0F1-1-1	-4	50	25	22	11
T0F2-2	150	62	45	-	-
T1F0	62	42	13	-22	-15
T1F1	108	70	37	-	-
T1F2	142	88	31	2	-
T1F1-1-1	142	73	31	-	-6
T1F2-2	169	97	44	33	-
T2F0	285	105	43	18	-
T2F1	258	140	70	-	-
T2F2	342	168	65	-	-
T2F1-1-1	354	162	95	32	-
T2F2-2	338	185	82	36	-

5.2.3 Diameter Distribution

Treatment differences in diameter distributions are compared graphically in terms of stand basal area per 5-cm DBH class (Figures 3–5). A comparison of these distributions indicated that:

1. In all thinning treatments, there was a shift in basal area from the smaller DBH classes to the larger, due to fertilization.
2. In the T0 treatment, the greatest basal area was in the 15-cm DBH class at the F0, F1, and F2 levels, and in the 20-cm DBH classes at the F2-2 and F1-1-1 levels.
3. In the T1 treatment, the greatest basal area was in the 20-cm DBH class in all the fertilizer levels, except for F2-2 level where the greatest basal area was in the 25-cm DBH class.
4. In the T2 treatment, the greatest basal area was in the 25-cm DBH class in the F0, F1, and F1-1-1 levels, and in the 30-cm DBH class in the F2 and F2-2 levels.

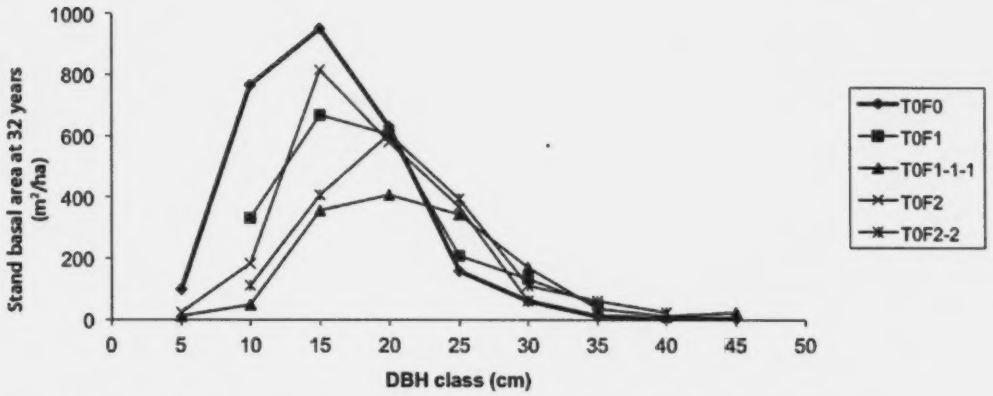

Figure 3. Distribution of stand basal area per hectare at year 32 by 5-cm DBH classes for the T0 treatment.

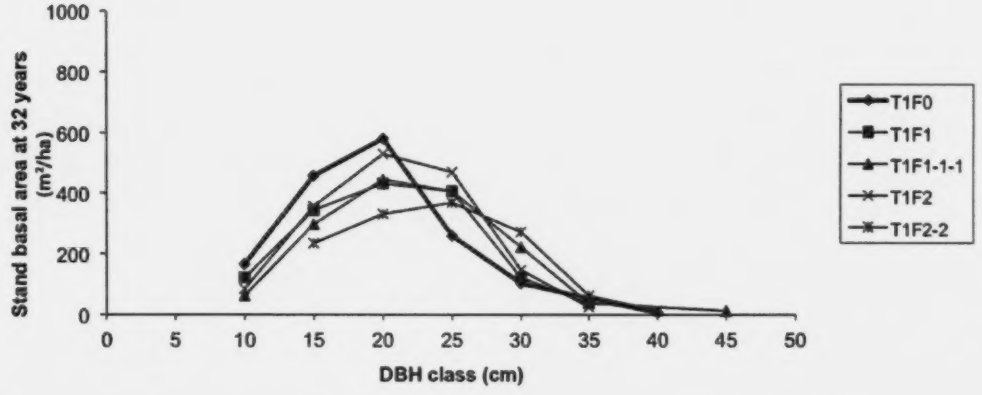

Figure 4. Distribution of stand basal area per hectare at year 32 by 5-cm DBH classes for the T1 treatment.

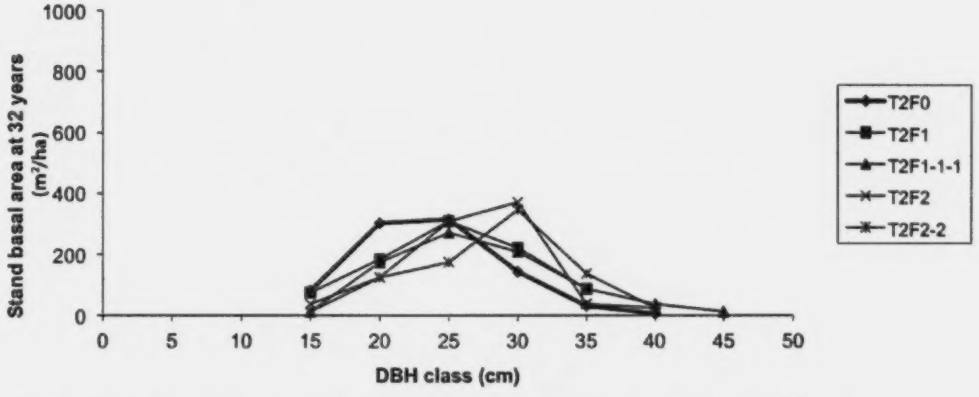

Figure 5. Distribution of stand basal area per hectare at year 32 by 5-cm DBH classes for the T2 treatment.

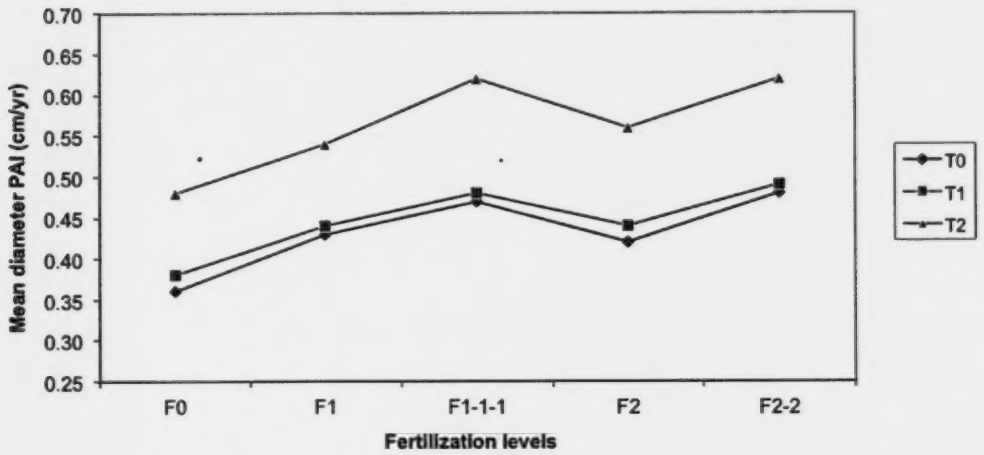

Figure 6. Adjusted crop tree average DBH (AAD) periodic annual increment (PAI) treatment means (250 trees/ha) for each treatment.

5.2.4 Crop Tree Diameter

The comparison of the treatment crop tree average DBH PAI showed that (Table 6):

1. There was no significant interaction between thinning and fertilization.
2. There were mixed results with both thinning and fertilization. Thinning and fertilization appeared to have a significant effect on average DBH PAI. The average DBH PAI increased with an increase in thinning intensity although there did not seem to be a difference between intensities for T0 and T1. Figure 6, showing average DBH PAI treatment means, indicates that thinning alone increased average DBH PAI more than fertilization alone.
3. The adjusted AAD PAI treatment means ranged from 0.36 cm/yr (T0F0) to 0.62 cm/yr (T2F2-2).

5.3 Height

5.3.1 Stand Height

Treatment differences in stand height were assessed in terms of AAH. Note that the differences in AAH are the result of the growth of survivor trees, tree mortality, and thinning. There is an immediate arithmetic effect when trees die or are thinned. If the trees removed are shorter than the average, the overall average AAH will increase, and if the trees removed are taller than the average, the overall average AAH will decrease. Top height comparisons were not made for the same reasons given by McWilliams and Therien (1996), who discuss that comparison of top height means, calculated using measured heights and heights estimated from height–diameter curves, may not be appropriate since the top height trees generally tend to be at the plot edges or are outside of the range of diameters used to develop the height–diameter equations.

The comparison of the treatment AAH PAI and 32-year AAH showed that (Table 6):

1. There was no significant interaction between thinning and fertilization.
2. Both thinning and fertilization had a significant effect on AAH PAI. The average AAH PAI increased with an increase in thinning intensity and with an increase in fertilizer dosage (Figures 7 and 8).
3. The adjusted AAH PAI treatment means ranged from 0.29 cm/yr (T0F0) to 0.51 cm/yr (T2F2-2), and the AAH at 32 years ranged from 18.0 m (T0F0) to 26.5 m (T2F2-2).

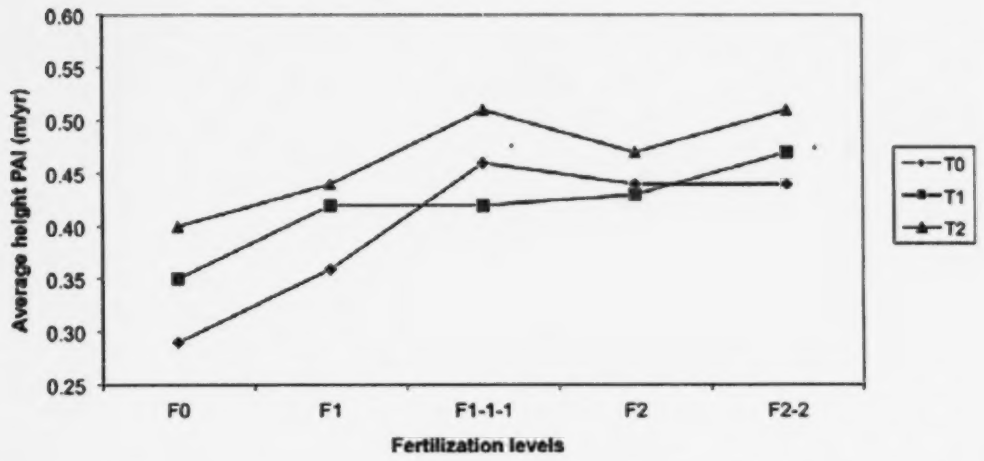

Figure 7. Adjusted arithmetic average height (AAH) periodic annual increment (PAI) treatment means for each treatment.

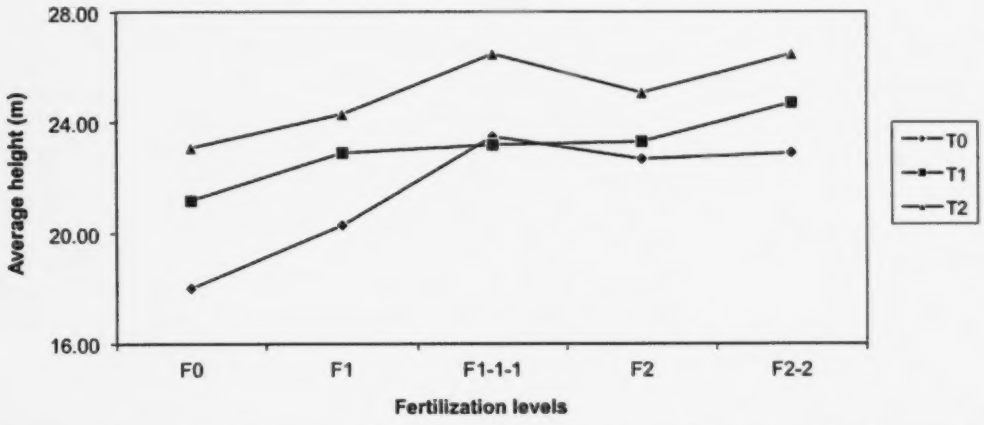

Figure 8. Adjusted arithmetic average height (AAH) treatment means, 32 years after treatment, for each treatment.

5.3.2 Trees of Similar Initial Height Classes

The unadjusted treatment means of 32-year periodic height growth of surviving trees are shown by initial 2-m height classes in Table 9. These data suggested that:

1. Height growth was greater at larger initial height classes.
2. Within each thinning level and initial height class, height growth was greater at higher fertilizer dosages.
3. Within each fertilization and initial height class, height growth was greater at higher thinning intensity.

5.3.3 Crop Tree Height

The comparison of the treatment crop tree average height PAI showed that (Table 6):

1. There was no significant interaction between the thinning and fertilization treatments.
2. Both thinning and fertilization had a significant effect on average height PAI. The average height PAI increased with an increase in thinning intensity and with an increase in fertilizer dosage (Figure 9).
3. The adjusted average height PAI treatment means ranged from 0.31 cm/yr (T0F0) to 0.54 cm/yr (T2F1-1-1).

Table 9. Arithmetic average height periodic increment (m/32 years) of surviving trees by initial 2-m total height classes.

Treatment	2-m Initial Total Height Class						
	4	6	8	10	12	14	16
T0F0	9.7	6.7	6.3	8.2	9.4	9.1	12.4
T0F1	-	6.8	8.7	10.1	11.6	12.1	-
T0F2	-	8.8	11.9	12.8	14.5	-	-
T0F1-1-1	8.7	-	9.2	13.0	13.9	14.6	17.2
T0F2-2	-	10.1	12.4	12.9	12.5	16.8	-
T1F0	8.7	10.8	7.9	10.8	11.5	11.5	-
T1F1	-	9.4	12.3	12.7	13.8	14.1	-
T1F2	-	10.3	12.2	13.1	13.1	14.5	-
T1F1-1-1	-	-	11.4	12.8	14.1	15.4	15.9
T1F2-2	-	-	14.4	13.7	15.4	15.7	-
T2F0	-	11.4	12.1	12.9	12.5	13.9	-
T2F1	-	-	12.3	14.4	14.6	15.6	-
T2F2	-	13.5	14.5	15.2	14.4	11.7	-
T2F1-1-1	-	14.3	15.2	15.9	17.3	17.4	-
T2F2-2	-	-	14.8	16.6	16.2	16.9	-

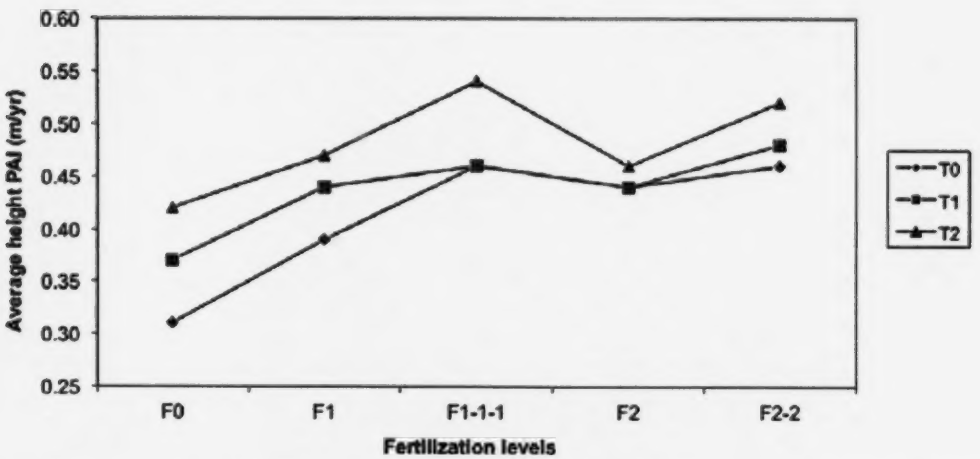

Figure 9. Adjusted crop tree arithmetic average height (AAH) periodic annual increment (PAI) treatment means for each treatment.

5.3.4 Live Crown Length

The unadjusted treatment means of tree live crown length (total height - HTLC), as a percent of total height, for Douglas-fir 32 years after treatment, are given in Table 10 by 4-m current total height classes. These data suggest that:

1. Average percent live crown length is greater at taller height classes.
2. Within each thinning level and height class, the longest live crowns are in the unfertilized treatments. The live crown lengths decreased with an increase in fertilizer dosage for all height classes (Figures 10–13).
3. Among the thinning levels, the longest live crowns were in the T2 treatment; the T0 and T1 treatments were similar to each other.

Table 10. Average live crown length as a percent of total height (%) for Douglas-fir, 32 years after initial treatment, by 4-m total height classes.

Treatment	4-m Total Height Class						
	8	12	16	20	24	28	32
T0F0	-	25	24	31	35	-	-
T0F1	-	27	23	23	31	43	-
T0F2	15	-	23	27	28	32	-
T0F1-1-1	-	-	18	21	27	34	-
T0F2-2	-	-	16	22	29	38	44
T1F0	-	31	24	26	32	-	-
T1F1	-	-	21	24	31	39	-
T1F2	-	-	25	25	29	50	-
T1F1-1-1	-	-	20	19	28	32	40
T1F2-2	-	-	-	26	22	31	37
T2F0	-	-	37	37	41	43	-
T2F1	-	-	29	30	36	37	40
T2F2	-	-	-	31	33	35	-
T2F1-1-1	-	-	-	34	35	38	39
T2F2-2	-	-	-	26	32	37	42

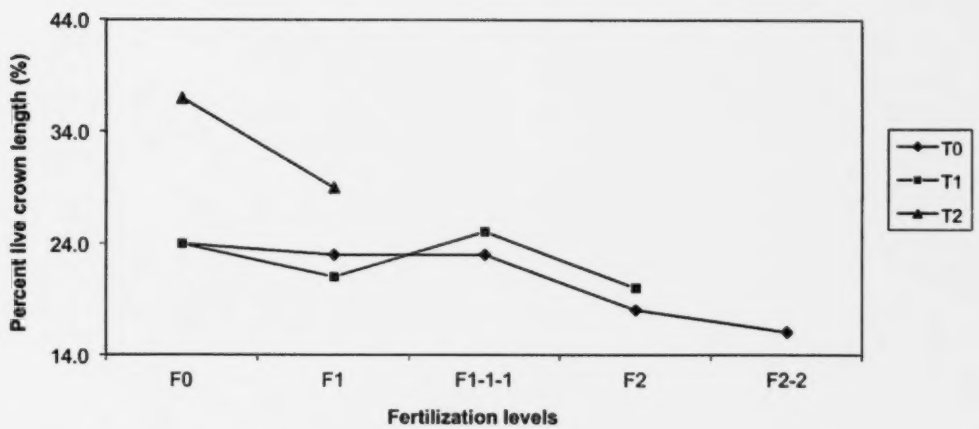

Figure 10. Average live crown length as a percent of total height for 16-m height class, 32 years after treatment, for each treatment.

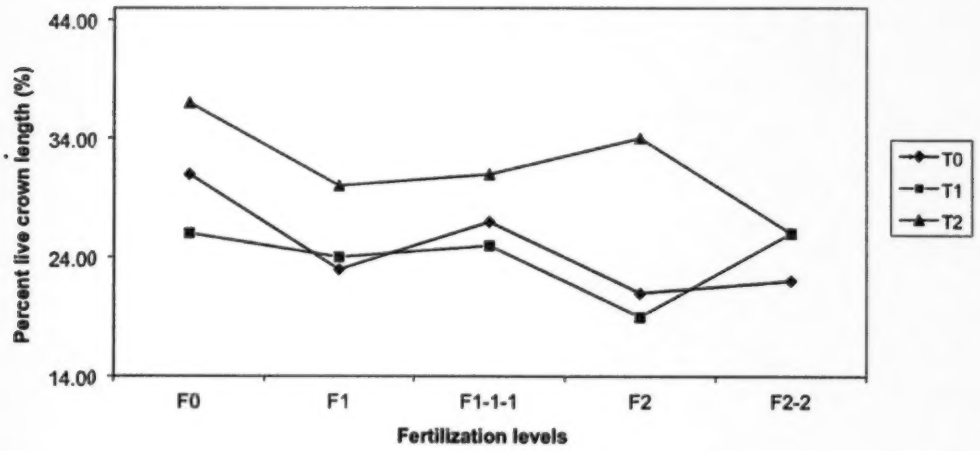

Figure 11. Average live crown length as a percent of total height for 20-m height class, 32 years after treatment, for each treatment.

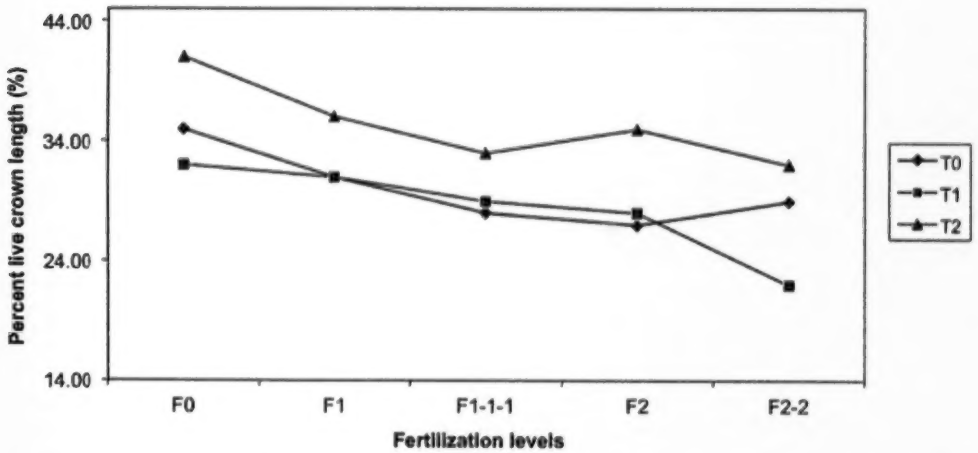

Figure 12. Average live crown length as a percent of total height for 24-m height class, 32 years after treatment, for each treatment.

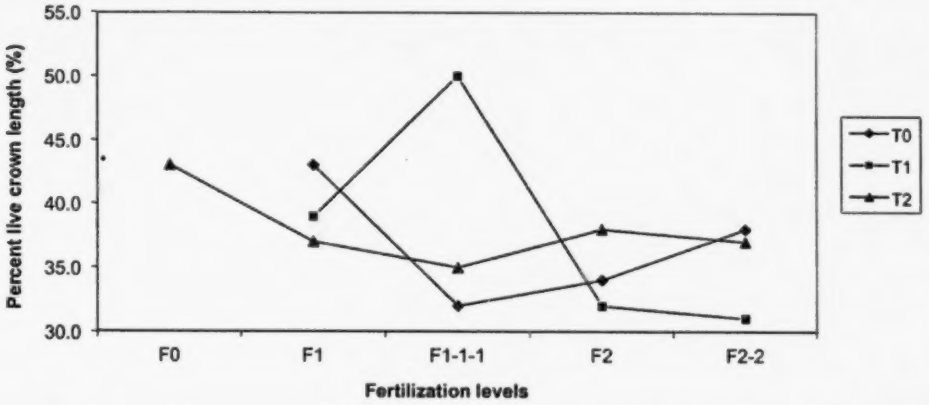

Figure 13. Average live crown length as a percent of total height for 28-m height class, 32 years after treatment, for each treatment.

5.4 Total Volume

5.4.1 Stand Volume

The unadjusted total volume treatment statistics are given in Table 11. The comparison of the treatment total volume PAI and 32-year volume showed that (Table 6):

1. There was no significant interaction between thinning and fertilization.
2. Fertilization had a significant effect on total volume PAI and 32-year total volume. There was greater total volume PAI and 32-year total volume at higher fertilizer dosages (Figures 14 and 15).
3. Thinning did not have a significant effect on either total volume PAI or 32-year volume. However, these results are confounded by post-treatment volume differences, the slower growth of more numerous smaller trees in the unthinned plots, and the faster growth of fewer larger trees in the thinned plots.
4. The total volume PAI treatment means ranged from 9.7 m^3/ha/yr (T0F0) to 16.3 m^3/ha/yr (T0F2-2), and the 32-year total volume ranged from 372 m^3/ha (T2F0) to 613 m^3/ha (T0F2-2). The total volume periodic growth per tree ranged from 0.13 m^3/32 yrs (T0F0) to 0.60 m^3/32 yrs (T2F2-2) (Figure 16).

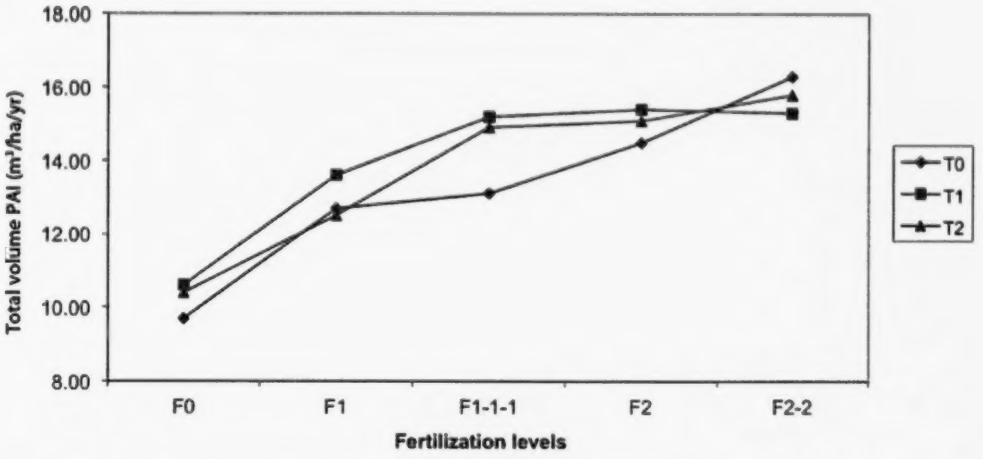

Figure 14. Adjusted total volume periodic annual increment (PAI) for each treatment.

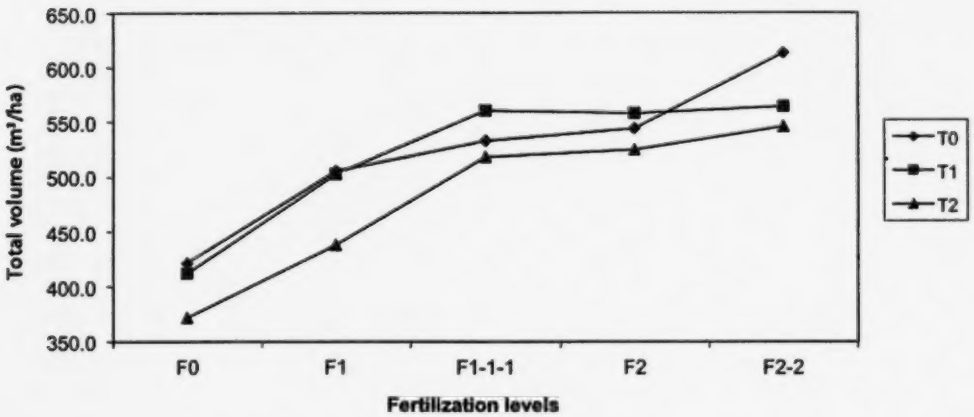

Figure 15. Adjusted total volume per hectare at 32 years for each treatment.

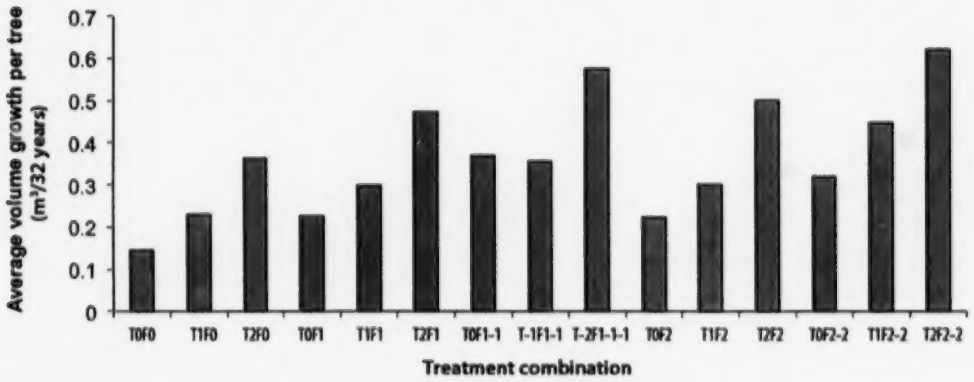

Figure 16. Average total volume growth per tree for each treatment combination.

5.4.2 Crop Tree Total Tolume

The unadjusted crop tree total volume treatment statistics are given in Table 12. The comparison of the treatment crop tree total volume PAI showed that (Table 6):

1. There was no significant interaction between thinning and fertilization.
2. Both thinning and fertilization had a significant effect on total volume PAI. There were mixed results in crop tree total volume PAI. F2 was actually lower than F1 in the T0 and T1 treatments, and F2-2 did not appear any greater with an increase in fertilizer dosage (Figure 17).
3. The adjusted total volume PAI treatment means ranged from 2.66 m^3/ha/yr (T0F0) to 6.80 m^3/ha/yr (T2F1-1-1).

Table 11. Unadjusted crop tree total volume 32-year periodic growth.

	250 Crop Trees		
Treatment	**0-yr (m^3/ha)**	**32-yr (m^3/ha)**	**Growth (m^3/ha/32 yrs)**
T0F0	21	116	95
T0F1	24	155	131
T0F2	13	117	104
T0F1-1-1	27	207	180
T0F2-2	20	175	155
T1F0	21	126	105
T1F1	18	148	130
T1F2	16	134	118
T1F1-1-1	22	185	163
T1F2-2	21	190	169
T2F0	17	147	130
T2F1	16	176	160
T2F2	16	180	164
T2F1-1-1	18	229	211
T2F2-2	18	228	210

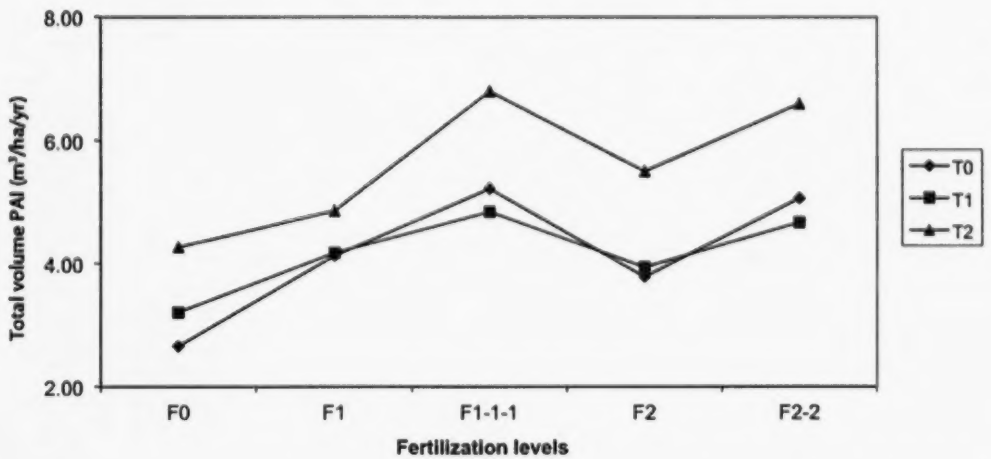

Figure 17. Adjusted crop tree total volume periodic annual increment (PAI) treatment means (250 trees/ha) for each treatment.

5.5 Merchantable Volume

5.5.1 Stand Merchantable Volume

The unadjusted merchantable volume treatment statistics are given in Table 11. The results of the comparison of the treatment merchantable volume PAI and 32-year volume are similar to those of total volume. From Table 6, comparisons of the probability values (*p*) from the fixed-effects model analysis showed that:

1. There was no significant interaction between thinning and fertilization.
2. Fertilization had a significant effect on merchantable volume PAI and 32-year volume. There was greater merchantable volume PAI and 32-year merchantable volume at higher fertilizer dosages (Figures 18 and 19).
3. Thinning did not have a significant effect on merchantable volume PAI or 32-year volume. However, the stand volume results are confounded by post-treatment volume differences, the slower growth of more numerous smaller trees in the unthinned plots, and the faster growth of fewer larger trees in the thinned plots.
4. The merchantable volume PAI treatment means ranged from 9.7 m^3/ha/yr (T0F0) to 16.1 m^3/ha/yr (T0F2-2), and the 32-year merchantable volume ranged from 318 m^3/ha (T0F0) to 531 m^3/ha (T0F2-2).

Table 12. Unadjusted total and merchantable volume (m^3/ha) for years 0 and 32, and net volume annual growth during the 32-year period (m^3/ha/yr).

	Total Volume				Merchantable Volume			
Treatment	**0 (Before)**	**0 32- (After)**	**Net Year**	**0 Growth**	**0 (Before)**	**32- (After)**	**Net Year**	**Growth**
T0F0	116	116	452	10.5	16	16	338	10.1
T0F1	100	100	504	12.6	21	21	416	12.3
T0F2	72	72	491	13.1	4	4	404	12.5
TOF1-1-1	118	118	569	14.1	31	31	503	14.8
T0F2-2	90	90	594	15.8	15	15	517	15.7
T1F0	104	72	419	10.8	18	15	252	7.4
T1F1	94	65	491	13.3	17	12	426	12.9
T1F2	87	61	534	14.8	10	8	466	14.3
T1F1-1-1	114	77	587	15.9	29	22	521	15.6
T1F2-2	131	83	623	16.9	38	18	564	17.1
T2F0	91	37	354	9.9	19	8	320	9.8
T2F1	107	40	451	12.8	19	7	414	12.7
T2F2	80	37	487	14.1	10	8	449	13.8
T2F1-1-1	89	39	497	14.3	11	9	461	14.1
T2F2-2	98	39	542	15.7	18	10	505	15.5

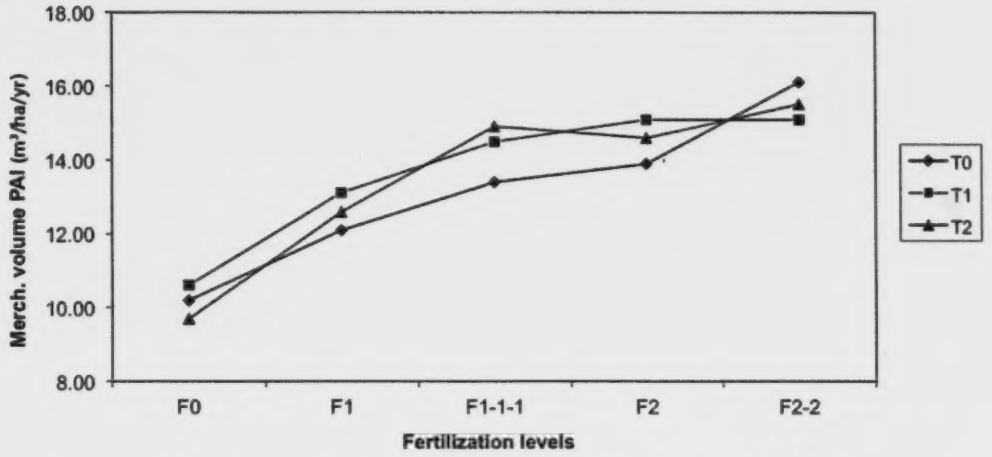

Figure 18. Adjusted merchantable volume periodic annual increment (PAI) at 32 years for each treatment.

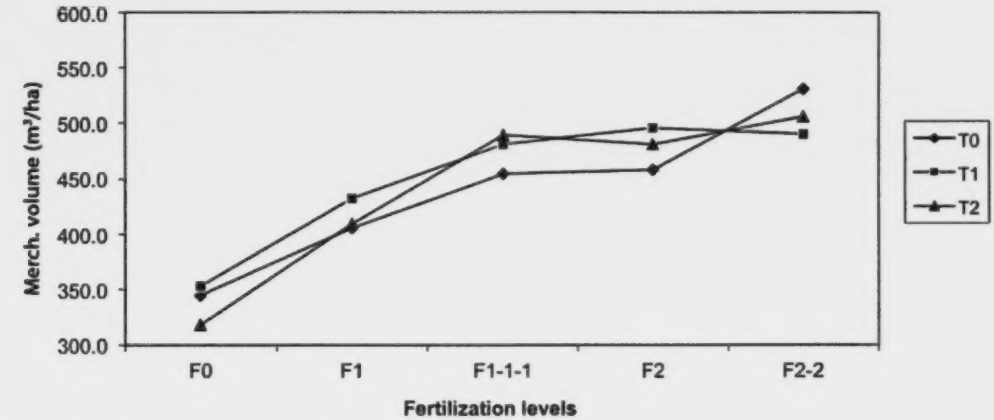

Figure 19. Adjusted merchantable volume per hectare at 32 years for each treatment.

5.5.2 Crop Tree Merchantable Volume

The unadjusted merchantable volume treatment statistics are given in Table 13. The comparison of the treatment crop tree merchantable volume PAI showed that (Table 6):

1. The interaction between the thinning and fertilization treatments was significant ($p = 0.03$).
2. Both thinning and fertilization had a significant effect on merchantable volume PAI. It appears that thinning above a critical point improves crop tree merchantable volume PAI, and 32-year yield increased with an increase in thinning intensity. However, T0 and T1 are similar enough that they would not likely be significantly different with an increase in fertilizer dosage (Figure 20).
3. The F1-1-1 treatment produced the greatest merchantable volume growth compared to all other treatments. The adjusted merchantable volume PAI treatment means ranged from 3.03 m^3/ha/yr (T0F0) to 7.01 m^3/ha/yr (T2F1-1-1).

Table 13. Unadjusted crop tree merchantable volume 32-year periodic growth.

	250 Crop Trees		
Treatment	**0-yr (m^3/ha)**	**32-yr (m^3/ha)**	**Growth (m^3/ha/32 yrs)**
T0F0	13	106	93
T0F1	17	145	128
T0F2	21	195	174
T0F1-1-1	4	107	103
T0F2-2	12	164	152
T1F0	13	116	103
T1F1	8	137	129
T1F2	16	174	158
T1F1-1-1	8	124	117
T1F2-2	14	178	164
T2F0	8	137	129
T2F1	6	165	159
T2F2	8	216	208
T2F1-1-1	7	169	162
T2F2-2	9	215	206

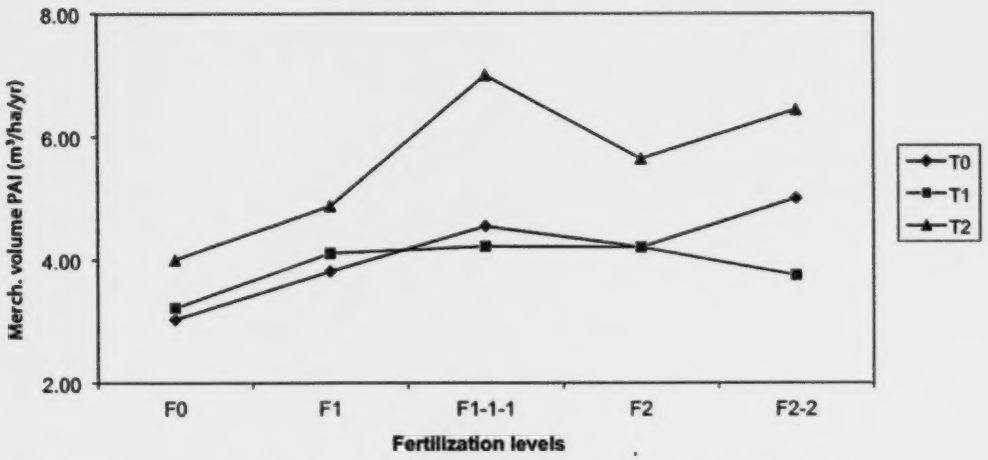

Figure 20. Adjusted merchantable volume periodic annual increment (PAI) of crop trees for each treatment.

6. Discussion

6.1 Fertilization and Thinning Effects on Stand Development

Across all thinning levels, fertilization accelerated stand development. In the T0 and T1 thinning levels, fertilization increased mortality rates. Fertilization did not affect mortality rates in the T2 treatments. Fertilization also affected stand structure. In particular, the T0F1-1-1 and T0F2-2 treatments altered the distribution of stems in terms of both diameter and height when compared to the T0F0 treatment. For example, in the T0F1-1-1 treatment there was 61% mortality, and at year 32 the remaining stems were apportioned 0, 0, 2, 17, 49, 30, and 2% in the 8, 12, 16, 20, 24, 28, and 32-m height classes respectively. By comparison, in the T0F0 treatment there was 44% mortality and the remaining stems were distributed 1, 5, 40, 45, 7, 2, and 0% in the respective height classes.

6.2 Response to Fertilization

The fertilizer response discussed here includes both direct and indirect response. Over the 32 years since the initial treatments, the ranking of total volume and merchantable volume per hectare within each thinning level was similar to that in year 24; it was F2-2 > F1-1-1 > F2 > F1 > F0. Ranking of fertilizer efficiency, in terms of total volume growth over the 32-year period, is similar to that over the 24-year period. Efficiency decreased with increasing fertilizer dosage (F1 > F2 > F1-1-1 > F2-2). These efficiencies were, in general, found with all of the thinning treatments, 1.8, 1.1, 0.7, and 0.6 m^3/ha/32-year/kg N/ha respectively. Note, however, that the volume growth responses were higher at higher fertilizer dosages. The total volume growth responses over the 32-year period were, in general, found with all of the thinning treatments, 26, 41, 48, and 55% for F1, F1-1-1, F2, and F2-2 respectively.

The ranking of average tree size, 32 years after initial treatment, were:

1. Total volume per tree: F2-2 > F1-1-1 > F2 > F1 > F0 (0.50, 0.47, 0.37, 0.36, and 0.23 m^3/tree respectively; adjusted values averaged within each treatment for all thinning treatments).
2. Quadratic mean DBH: F2-2 > F1-1-1 > F2 > F1 > F0 (24.1, 23.7, 23.2, 21.9, and 20.3 cm respectively; adjusted values averaged within each treatment for all the thinning treatments). The largest quadratic mean DBH was in the T2F2-2 treatment (28.3 cm, adjusted mean), which was almost twice that of the smallest (16.8 cm at T0F0).
3. Arithmetic average height: F2-2 > F1-1-1 > F2 > F1 > F0 (24.7, 24.4, 23.7, 22.5, 20.8 m respectively; adjusted values averaged within each treatment for all thinning treatments). The tallest trees were 26.5 m in the F2-2 treatment compared to 18.0 m in the T0F0.

Note that some of the differences in quadratic mean DBH and arithmetic average height between the thinning treatment and the T0 treatment are due to the arithmetic increase that results from thinning and mortality over time. The average diameter and height growth was greatest for the large trees and decreased with decreasing initial diameter classes.

6.3 Response to Thinning

Thirty-two years after the initial treatments, the ranking of total volume per hectare remains the same as at 24 years: T0 > T1 > T2. However, the differences between the thinning treatments and the unthinned treatment continue to narrow, especially in the T2 treatment. The differences decreased from 3% at year 24 to 2% at year 32 for the T1 treatment, and from 19% to 12% for the T2 treatment. The ranking of merchantable volume per hectare (≥ 12.5 cm DBH) at year 32 was T1 > T2 > T0, which is different from the ranking at year 24 (T1 > T0 > T2).

The rankings of average tree size, 32 years after initial treatment, were:

1. Total volume per tree: T2 > T1 > T0 (0.17, 0.27, and 0.40 m^3/tree respectively; adjusted values averaged within each treatment for all fertilization treatments).
2. Quadratic mean DBH: T2 > T1 > T0 (24.1, 20.1, and 16.8 cm respectively; adjusted values). The average diameter growth was greatest for the large trees and decreased with decreasing initial diameter classes.
3. Arithmetic average height: T2 > T1 > T0, (23.1, 21.2, and 18.0 m respectively; adjusted values averaged within each treatment for all fertilization levels). The average height growth was greatest for the larger trees and decreased with decreasing initial DBH classes. Average

height growth of all trees, crop trees, and the growth across initial height classes increased with both thinning and fertilization.

4. For the 250 crop trees, averaged across all fertilizer levels, the greatest height growth was in the T2 treatment (16 m/32 yrs) followed by T1 (14 m/32 yrs) and T0 (9 m/32 yrs).

Note that some of the differences in quadratic mean DBH and arithmetic average height between the thinning treatment and the T0 treatment are due to the arithmetic increase that results from thinning and mortality over time.

6.4 Comparisons with Previous Results

The 32-year results are comparable to the trends reported in the 24-year response report (McWilliams and Therien 1996). Compared to the 24-year results:

1. The ranking of mortality rates remained the same (T0 > T1 > T2), and the main cause of the mortality continued to be suppression.
2. Diameter growth trends were similar.
3. There was no significant interaction between the thinning and fertilization treatments for individual tree average height (AAH) PAI and 32-year AAH. However, McWilliams and Therien (1996) detected an interaction. The difference in these results is probably because we used average plot values rather than individual tree measurements.
4. The live crown lengths, relative to total height, were shorter than at year 24.
5. Basal area, total volume, and merchantable volume trends and rankings were similar. However, unlike McWilliams and Therien (1996), we detected significant differences in pre-treatment total and merchantable volume and, therefore, had to adjust the treatment means.
6. The gap between the basal area and volume yield in the thinned and unthinned treatments is continuing to narrow over time. At year 32, the only thinned treatments with less total volume than the unthinned control were T1F0 and T2F0. The T2F1 treatment, which had less total volume at year 24, now has more volume than the control.

7. Conclusions

The analysis results were generally consistent with our expectations. The results showed the following:

1. Cumulative mortality over the 32-year period since the initial treatment was highest in the T0 and T1 treatments, and negligible in the T2. The main cause of mortality continues to be suppression, although snow damage was also prevalent. Thus, thinning can be beneficial by capturing the trees that would otherwise have been lost to mortality, if the fibre from the thinned trees can be used.
2. Fertilization increased stand and crop tree diameter and height PAI in both thinned and unthinned stands, with greatest growth in the T2F2-2 treatment.
3. Thinning also increased stand diameter and height PAI, and shifted stand basal area to fewer, larger-diameter trees. However, part of this increase is due to the arithmetic increase in average diameter or height resulting from the removal of smaller-than-average trees through thinning and mortality.
4. Heavy thinning increased the live crown length, and fertilization slightly decreased the live crown length. That is, the amount of clear bole was reduced by heavy thinning. Thus, thinning may have to be combined with pruning to reduce the number of knots on the bole, if the management objective is lumber production.
5. Both fertilization and thinning produced trees that were larger in diameter, taller, and had more total volume per tree.
6. Fertilization increased production of stand and crop tree total and merchantable volume in both thinned and unthinned stands, with the greatest growth in the F2-2 treatment. For example, the total volume PAI responses relative to F0 ranged from 26% (F1) to 55% (F2-2). However, the F1 treatment was the most efficient in terms of total volume PAI per kg N/ha.
7. Thinning did not have a significant effect on stand total and merchantable volume production, although heavy thinning significantly increased crop tree total and merchantable volume PAI. However, the stand volume results are confounded by post-treatment volume differences, the slower growth of more numerous smaller trees in the unthinned plots, and the faster growth of fewer larger trees in the thinned plots. The ranking of total volume/ha at 32 years was T0 > T1 > T2, although

the gap between total volume in the thinned and the unthinned stands is narrowing.

These 32-year results have added to the information base supporting informed forest management decision-making in coastal British Columbia, and contribute to the Canadian Wood Fibre Centre's initiative of promoting research on the effect of silviculture and stand dynamics on fibre-attribute value. They will also contribute to our knowledge of the mechanics of coastal Douglas-fir response to thinning and fertilization.

Further study is now required to examine both the economic implications of this study and the applicability of the results of this study to areas with different site conditions. It appears that the results of this study can only be extended to similar moderately dry, nutrient-poor to -medium sites; and we therefore suggest that such sites be the focus of further study.

8. Literature Cited

Barclay, H.; Brix, H.; Layton, C.R. 1982. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 9-year growth response. Environment Canada, Canadian Forestry Service, Pacific Forest Research Centre, Victoria, BC. Information Report BC-X-238.

Barclay, H.; Brix, H. 1985. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 12-year growth response. Agriculture Canada, Ministry of State for Forestry, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-271.

Brix, H. 1993. Fertilization and thinning effect on a Douglas-fir ecosystem at Shawnigan Lake: A synthesis of project results. BC Ministry of Forests, Research Branch, Victoria, BC. FRDA Report No.196.

Bruce, D. 1981. Consistent height-growth and growth-rate estimates for remeasured plots. Forest.Science 27(4):711–725.

Crown, M.; Brett, C.P. 1975. Fertilization and thinning effect on a Douglas-fir ecosystem at Shawnigan Lake: An establishment report. Environment Canada, Canadian Forest Service, Pacific Forest Research Centre, Victoria, BC. Information Report BC-X-110.

Crown, M.; Quenet, R.V.; Layton, C.R. 1977. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 3-year growth response. Government of Canada, Department of the Environment, Canadian Forest Service, Pacific Forest Research Centre, Victoria, BC. Information Report BC-X-152.

Gardner, E.R. 1990. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 15-year growth response. Forestry Canada, Pacific and Yukon Region, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-319.

Hall, T.H.; Quenet, R.V.; Layton, C.R.; Robertson, R.J. 1980. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 6-year growth response. Canadian Forestry Service, Pacific Forest Research Centre, Victoria, BC. Information Report BC-X-202.

Little, R.C.; Milliken, G.A.; Stroup, W.W.; Wolfinger, R.D. 1996. SAS system for mixed models. SAS Institute Inc., Cary, NC.

McWilliams, E.R.G.; Therien. G. 1996 (revised 1997). Fertilization and thinning effect on a Douglas-fir ecosystem at Shawnigan Lake: 24-year growth response. BC Ministry of Forests, Research Branch, and Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. FRDA Report No. 269.

Omule, S.A.Y. 2008. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 32-year growth response. BC Forest Science Program, Project Y081189: Analysis and reporting of the Shawnigan Lake fertilizer and thinning effect. Victoria, BC. http://www.for.gov.bc.ca/hfd/library/FIA/2008/FSP_Y081189b.pdf. Appendices: http://www.for.gov.bc.ca/hfd/library/FIA/2008/FSP_Y081189a.pdf (Accessed February 10, 2011)

Omule, S.A.Y.; Fletcher, V.E.; Polsson, K.R. 1987. Total and merchantable volume equations for small coastal Douglas-fir. BC Ministry of Forests and Lands, Research Branch, Victoria, BC. FRDA Report No. 010.

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